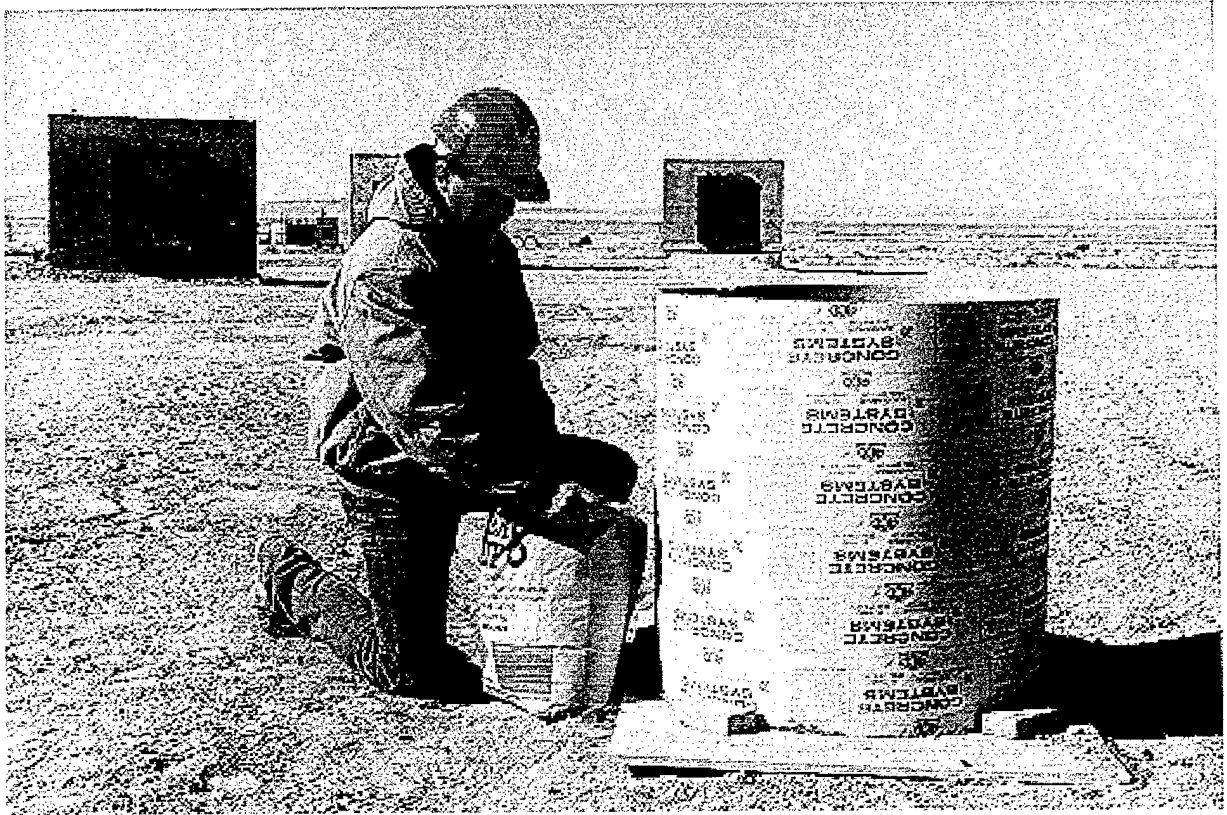


# Mitigation of Glass Fragment Hazards In Terrorist Bombings



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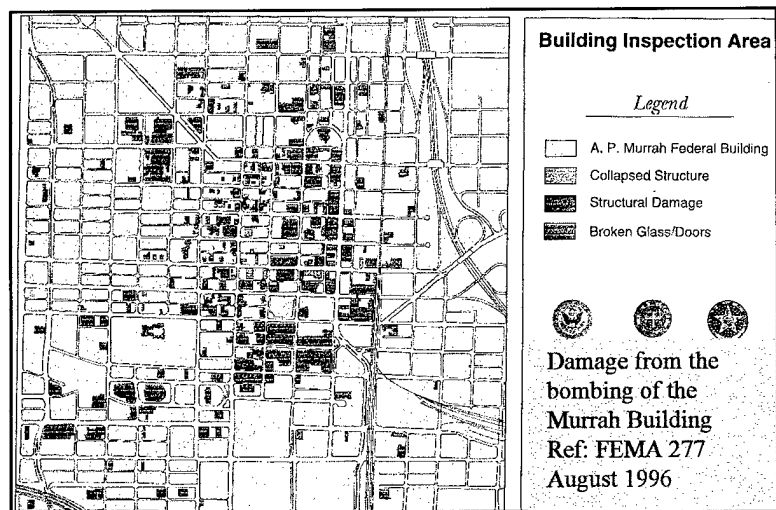
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## Mitigation of Glass Fragment Hazards In Terrorist Bombings

Propelled by the forces of a terrorist bomb, glass fragments may cause large numbers of serious injuries. While heavy structural damage and collapse is generally local in nature, even for a large bomb like that used in Oklahoma City, hazardous glass fragments may pose significant hazards to people in areas far removed from the attack. This is illustrated in the damage survey at the right.



Window systems consist of the glass pane, gaskets and sealants, the window frame and the anchorage to the supporting wall surface. In order to achieve a given measure of blast resistance, it is imperative that the entire window system be designed to balance the relative capacities of the system components. For example, it makes little sense and may actually introduce additional hazard to design a window system in which the glazing is stronger than the supporting frame or its attachment to the building. In such a case, the glazing may pop out and the entire assembly may be thrown into occupied spaces. A balanced design is required.

The blast capacity of glass, that is the pressure and impulse necessary to cause the glass to fail, is controlled by the type and thickness of the glass and the size of the window opening. Assuming that a window system design is balanced, thicker glass panes will provide higher blast capacities. Likewise, blast capacity is increased as the size of the window opening decreases. Glass material type will also influence capacity. Thermally tempered glass (TTG), for example, has a breaking strength that is approximately twice that of heat strengthened glass (HSG) and nearly four times that of annealed glass (AG). Glass type also influences potential hazards of the glass fragments and shards after glass failure. TTG, for example, will fail in smaller clumps or cube shaped fragments that generally pose a lower hazard than the dagger like shards produced from failing annealed glass. Hence, one effective approach to reducing the potential hazards from window glass is to design fewer and smaller windows with thicker and stronger glass that fails with lower hazard fragment sizes and shapes.

Blast resistant window technology and design procedures are readily available. Such windows have been designed and built for the military, the State Department, and other Government agencies as well as commercial/industrial users for many years. Truly blast

resistant windows that are designed to fully resist a blast event provide the highest level of security and safety. However, they tend to be limited in size, expensive and are not always aesthetically pleasing. Hence, while available, fully blast resistant windows may not be practical when the goal is to provide a measure of protection to many hundreds of public buildings. As members of a free and open democratic society we expect and demand that our approach to security not be oppressive or reflect a bunker-like mentality.

With the heightened concern about terrorism in this country and the perceived need to protect not only limited high value target facilities but many facilities, an urgent need was created to develop practical and affordable techniques to limit or mitigate the potential hazards from flying glass fragments and shards. In response to this need, the US Government and private industry are developing and testing new technologies to mitigate hazards to people in the vicinity of a terrorist bombing. In cooperation with the US Army Corps of Engineers (USACE), Defense Special Weapons Agency (DSWA), US General Services Administration (GSA) and several private companies, Applied Research Associates (ARA) conducted several tests to assess the capability of methods to reduce the hazards of flying glass shards after failure of the window system. Controlling post-failure behavior does not provide as great a level of protection as designing the windows to fully resist the blast forces, but this approach does provide a practical and prudent means of reducing potential risks.

Tests were conducted in 1996 through 1998 using C4 (a military plastic explosive) and ANFO (an easy to make improvised explosive). Mounted in enclosed concrete reaction structures, the window systems evaluated included annealed, heat treated, and thermally tempered glass encompassing a wide range of monolithic, laminated and insulated configurations. Both non-responding steel frames as well as commercially available aluminum frames were evaluated. High and normal speed photography in conjunction with active pressure measurements were used to document window responses. Control specimens with no protection were also included in the tests to demonstrate the potential hazards of uncontrolled glass failure. Other samples were retrofitted with single extrusion and multi-layer security window films of 4, 6, 7 and 11 mil thickness. Laminated glass was evaluated in deep rebated frames. Finally, blast curtains that are commonly used in the U.K. to catch glass fragments after failure were also evaluated. The tests included in this paper are described in Tables 1 and 2.

All tests were performed using the GSA's "Standard Test Method for Glazing and Glazing Systems Subject to Airblast Loadings." This test method was adapted from the methods presented in the ASTM method F1642-96. All windows tested were nominally 48 by 66 inches (pane dimensions) with a 46 by 64 inch clear opening. Witness panels were located 110 and 116 inches behind the windows in test series 1-3 and 4-7, respectively. These foam panels were used to record glass fragment impacts.

Table 1: Test location and blast description.

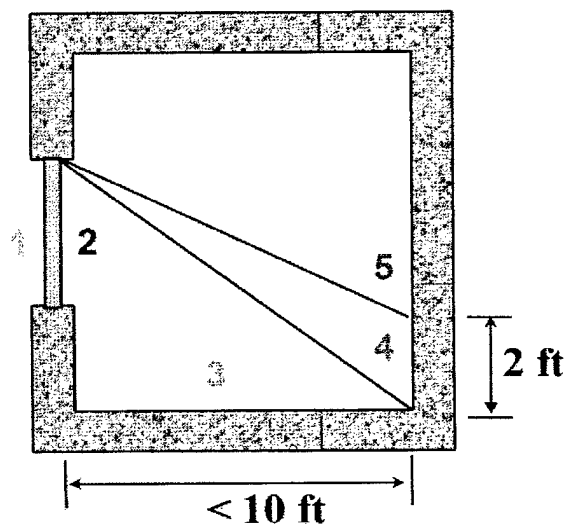
Test Series Location	Sponsor Test Conductor	Date	Explosive Charge
1. Fort Polk, LA	GSA USACE	July 8 – 18, 1996	420-lb, C4 (500 – lb TNT equivalent)
2. Fort Polk, LA	GlassLock USACE / ARA	August 12-22, 1996	420-lb, C4 (500 – lb TNT equivalent)
3. Fort Polk, LA	Monsanto USACE	August 29-30, 1996	420-lb, C4 (500 – lb TNT equivalent)
4. Kirtland AFB, NM	3M DSWA / ARA	January 12-19, 1998	600-lb, ANFO (500 – lb TNT equivalent)
5. Kirtland AFB, NM	GlassLock DSWA / ARA	January 22, 1998	600-lb, ANFO (500 – lb TNT equivalent)
6. Kirtland AFB, NM	Skyline Mills / Intellimar DSWA / ARA	January 26, 1998	600-lb, ANFO (500 – lb TNT equivalent)
7. Kirtland AFB, NM	GlassLock DSWA / ARA	March 5, 1998	600-lb, ANFO (500 – lb TNT equivalent)

Table 2: Description of windows tested.

Test Series Location	Number of Windows	Type of Windows	Glass thickness (in)
1	20	1. Monolithic TTG 2. Laminated TTG	1. ¼, 3/8, ½ 2. 1/8+1/8, 3/16+3/16, ¼+¼
2	20	1. Annealed (AG) 2. Thermally Tempered (TTG)	1. ¼, 3/8 2. ¼, 3/8, ½
3	8	1. Laminated AG 2. Monolithic AG 3. Laminated Heat Strengthened (HSG)	1. 1/8 + 1/8, insulated <sup>1</sup> 2. ¼, insulated <sup>1</sup> 3. 1/8+1/8, ¼+¼
4	24	1. Monolithic AG 2. Monolithic TTG 3. Monolithic Heat Strengthened (HSG)	1. ¼ 2. ¼, 3/8, ½, insulated <sup>2</sup> 3. ¼
5	4	1. Monolithic TTG 2. Monolithic HSG	1. ¼ 2. insulated <sup>2</sup>
6	4	1. Monolithic AG 2. Monolithic TTG	1. ¼ 2. ¼
7	4	1. Monolithic TTG 2. Monolithic AG	1. ¼ 2. ¼

Note: Insulated glass consists of: insulated<sup>1</sup> = ¼ - inch glass + ¼ - inch airspace + ¼ - inch glass  
insulated<sup>2</sup> = ¼ - inch glass + ½ - inch airspace + ¼ - inch glass

The GSA's glazing performance standard was used to evaluate the performance of the window specimens. This standard rates the potential hazards and protection level of window systems based on the post-event location of the glass fragments and shards. Fragments that enter occupied spaces at high velocity will travel further into the space and pose a higher level of hazard to occupants. Hence, the GSA performance standard indirectly rates the hazard of fragments based on the velocity of the fragments entering protected spaces. This standard is illustrated at the right.



GSA's method of evaluating the protection offered by various window configurations is similar to the rating schemes used by the British. The only significant differences are that the British scheme places condition 3 at a distance of one meter (3.3 ft) from the window and condition 4 at a distance of one-half meter above the floor. The five conditions shown indicate the location of fragments and/or shards after failure. The conditions are defined as follows:

Table 3: GSA protection levels (Ref: GSA Security Criteria – January 17, 1997).

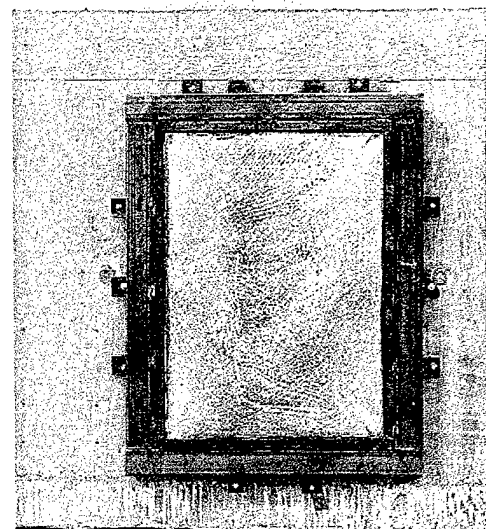
Condition	Protection - Hazard Level	Description
1	Very High Protection – No Hazard	Glass does not break.
2	Very High Protection – Very Low Hazard	Glass cracks but is retained by the frame.
3	High Protection – Low Hazard	Glass fails. Fragments enter space but land on floor no further than 10 ft from the window.
4	Medium Protection – Medium Hazard	Glass fails. Fragments enter space but land on floor or impact witness panel at a distance of 10 ft at a height no greater than 2 ft above the floor.
5	Low Protection – High Hazard	Glass fails catastrophically. Impacts on witness panel at a distance of 10 ft at a height more than 2 ft above the floor.

Twenty-one tests were performed and are reported in this paper. These tests included a total of 84 window test specimens. The results of the tests are briefly summarized in Table 4. The table presents a brief description of the test article, the window response in terms of the GSA protection condition in accordance with Table 3, and the pressure and impulse recorded during the test. Peak pressures ranged from 3.5 to 11.5 psi and impulses ranged from 23.9 to 50.5 psi-msec. Specimen responses ranged from 1 to 5 on the GSA scale. Details of the test results are available in the individual test series data analysis and test reports.

The hazard mitigation techniques evaluated showed significant potential for reducing the hazards from glass fragments. As expected, thermally tempered glass failed in a less hazardous manner than annealed or heat strengthened glass. Laminated glass and glass protected with mechanically attached film provided similar levels of protection under the tested conditions.

In general, the following are some major observations from the tests:

- Laminated glass can be engineered to withstand significant blast loads provided that adequate framing is provided. The failure mode for the laminated glass samples tended to be pull-out of the glass pane from the window bite.



Test Series 7 Window 1 Post Test: This ¼ inch thick TTG window was protected with a 7 mil thick film attached on four sides to the window frame. The glass broke but was retained by the film and the frame.

- Properly installed security window film provided significant hazard mitigation. Film generally performed better when applied to thermally tempered as opposed to annealed glass. The annealed glass at higher pressure levels initiated tears in the film which lowered the overall protection performance. Increasing film thickness generally improved the performance of the films evaluated. In addition, mechanically attached film provided better protection than daylight installed film especially at pressure levels above about 4 psi. In general, there was little observable difference in the performance of edge to edge film and daylight installed film for the limited number of samples examined. Finally, wet glazed film installations where the film is adhered to the window frame with a structural sealant appeared to provide high levels of protection.
- The blast curtain evaluated provided protection up to the tested 4 psi peak overpressure. The test results, shown on the last page of this paper (test series 6 window 3), achieved a GSA protection level 3. With additional engineering, the blast curtain technology may be capable of providing similar protection at higher blast environments. In addition, this technology may be used in conjunction with laminated glass and/or filmed glazing.

**Table 4: Results of explosive tests on various window systems.**

Test Series Location	Test No.	Window 1 Description GSA Condition	Window 2 Description GSA Condition	Window 3 Description GSA Condition	Window 4 Description GSA Condition	Nominal Peak Pressure (psi)/Impulse (psi-msec)	Stand off (ft)
1	1	¼" mono TTG, no PCM	1/8" + 1/8" Laminated TTG, no PCM	¼" mono TTG, 7 mil EE	¼" mono TTG, 7 mil 4-sided attachment	4.0/26.9	223
		3	2	3	2		
	2	3/8" mono TTG, no PCM	3/16" + 3/16" Laminated TTG, no PCM	3/8" mono TTG, 7 mil EE	3/8" mono TTG, 7 mil 4-sided attachment	6.0/38.9	170
		3	3	3	2		
	3	½" mono TTG, no PCM	¼" + ¼" Laminated TTG, no PCM	½" mono TTG, 7 mil EE	½" mono TTG, 7 mil 4-sided attachment	8.0/42.8	142
		3	1	3	3		
	4	¼" mono TTG, 7 mil EE	¼" mono TTG, 7 mil 4-sided attachment	1/8+1/8 Laminated TTG, no PCM	¼" mono TTG, 7 mil 4-sided attachment	5.0/33.6	191
		3	3	2	3		
2	1	¼" mono TTG, no PCM	¼" mono TTG, 7 mil 4-sided attachment	¼" mono AG, no PCM	¼" mono AG, 7 mil 4-sided attachment	3.5/23.9	247
		5	2	5	2		
	2	3/8" mono TTG, no PCM	3/8" mono TTG, 7 mil 4-sided attachment	½" mono TTG, no PCM	½" mono TTG, 7 mil 4-sided attachment	6.0/35.5	170
		3	1	1	1		

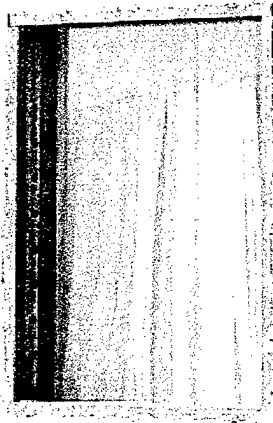
Test Series Location	Test No.	Window 1 Description GSA Condition	Window 2 Description GSA Condition	Window 3 Description GSA Condition	Window 4 Description GSA Condition	Nominal Peak Pressure (psi)/Impulse (psi-msec)	Stand off (ft)
2 (con't)	3	3/8" mono AG, no PCM	3/8" mono AG, 7 mil 4-sided attachment	3/8" mono TTG, no PCM	3/8" mono TTG, 7 mil 4-sided attachment	7.0/43.0	150
		5	3	5	2		
	4	1/4" mono AG, 7 mil day-light PCM	1/4" mono AG, 7 mil 4-sided attachment	1/4" mono TTG, 7 mil day-light PCM	1/4" mono TTG, 7 mil 4-sided attachment	5.0/30.8	191
		3	3	2	2		
	5	1/4" mono TTG, 7 mil 4-sided attachment	1/4" mono AG, 7 mil 4-sided attachment	1/4" mono TTG, 7 mil 2 vertical edges attached	1/4" mono TTG, 7 mil top edge attached	4.0/27.8	223
		2	3	2	2		
3	1	1/4" laminated AG, no PCM	1/4" laminated HSG, no PCM	1/4" mono AG + 1/4" air + 1/4" laminated AG	1/4" mono AG, no PCM	4.0/27.7	223
		2	2	2	5		
	2	1/2" laminated AG, no PCM	1/2" laminated HSG, no PCM	1/4" mono AG + 1/4" air + 1/4" laminated AG	1/4" laminated AG + 1/4" air + 1/4" laminated AG	8.0/48.9	133
		3	3	3	2		
4	1	1/4" mono AG, *4 mil day-light PCM	1/4" mono AG, *4 mil 4-sided attachment	1/4" mono AG, 7 mil 4-sided attachment	1/4" mono AG, no PCM	4.2/28.4	190
		3-SHR	3-SHR	3-SHR	5		
	2	1/4" mono HSG, *4 mil 4-sided attachment	1/4" mono TTG, *4 mil 4-sided attachment, aluminum frame	1/4" mono AG, *4 mil 4-sided attachment, aluminum frame	1/4" mono AG, *4 mil 2-sided vertical attachment	4.1/28.7	190
		3-SHR	3-SHR	5-SHR	3-SHR		
	3	1/4" mono TTG, *4 mil, 4-sided attachment	1/4" mono TTG, *6 mil, 4-sided attachment	1/4" mono HSG, *6 mil, 4-sided attachment	1/4" mono TTG, *4 mil, daylight	5.3/33.4	165
		3-SHR	2	3-SHR	3		
	4	1/4" mono AG, *6 mil, 4-sided attachment	1/4" mono TTG, *4 mil 4-sided wet glaze, aluminum frame	1/4" mono AG, *4 mil 4-sided wet glaze, aluminum frame	1/4" mono TTG, *4 mil 4-sided attachment	4.1/29.0	190
		3	2	3-SHR	3-SHR		
	5	3/8" mono TTG, *4 mil, 4-sided attachment	1/2" mono TTG, *6 mil, 4-sided attachment	1/2" mono TTG, *4 mil, 4-sided attachment	3/8" mono TTG, *4 mil, day-light	9.1/49.6	121
		3	2	5-SHR	3-SHR		
	6	1/4" mono TTG, *4 mil, daylight	1/4" mono TTG + 1/2" air + 1/4" mono TTG, *4 mil, 4-sided attachment	1/4" mono TTG + 1/2" air + 1/4" mono TTG, *6 mil, 4-sided attachment	1/4" mono TTG + 1/2" air + 1/4" mono TTG, no PCM	9.0/49.6	121
		5	3-SHR	2	5		

Test Series Location	Test No.	Window 1 Description GSA Condition	Window 2 Description GSA Condition	Window 3 Description GSA Condition	Window 4 Description GSA Condition	Nominal Peak Pressure (psi)/Impulse (psi-msec)	Stand off (ft)
5	1	1/4" mono TTG, 11 mil, 1-sided attachment	1/4" mono HSG + 1/2" air + 1/4" mono HSG, 7 mil, 2 sided vertical attachment, aluminum frame	1/4" mono HSG + 1/2" air + 1/4" mono HSG, 11 mil, 2 sided vertical attachment, aluminum frame	1/4" mono HSG + 1/2" air + 1/4" mono HSG, no PCM	8.7/48.2	124
		3-SHR	5	5-SHR	5		
6	1	1/4" mono AG, no blast curtain	Wood framed window with 1/4" mono AG, 3 x 2 true division window, exterior mounted curtain	1/4" mono AG, exterior mounted curtain	1/4" mono TTG, interior mounted curtain	Windows 1-3 4.0/28.8	190
		5	5	3	5	Window 4 11.5/50.5	110
7	1	1/4" mono TTG, 7 mil 4-sided attachment	1/4" mono AG, 4 mil day-light, aluminum frame	1/4" mono AG, 7 mil day-light, aluminum frame	1/4" mono TTG, no PCM	4.0/28.2	190
		2	3	3	5		

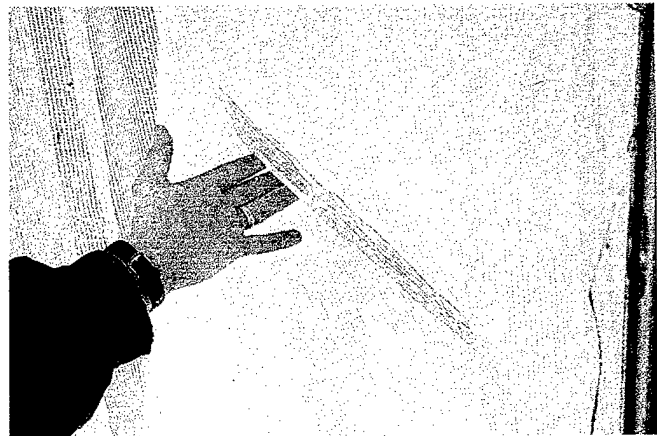
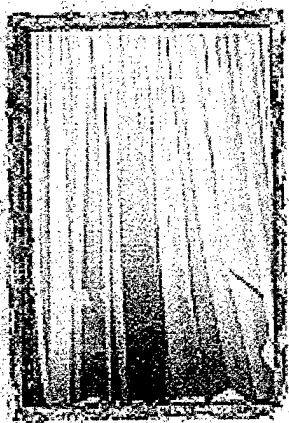
- PCM denotes Polyester Composite Material (i.e., security film). A \* denotes multi-layered film.
- Film is installed in several configurations. Daylight detonates film that is applied to the visible glass surface only. EE (Edge to Edge) denotes film that is installed to the edges of the glass pane and is captured in the bite of the window frame. Attached film is installed on the glass surface and mechanically fastened to the window frame by means of a batten bar system.
- The SHR stands for significant-hazard-reduction. This designation is used to distinguish a significantly reduced glass fragment hazard obtained with a protective window system versus a highly hazardous uncontrolled failure with no protective measure that is given the same GSA hazard condition. The SHR designation can be given for GSA conditions 3-5. The SHR designation was not used in test series 1-3.
- Unless otherwise indicated, all tested window frames are steel.

In conclusion, all of the hazard mitigation techniques (i.e., balanced window system design, appropriate selection of glass type and thickness, laminated glass, security window film and blast curtains) provided reductions in the hazards from glass fragments and shards. These methods should be employed by facility owners and occupants to reduce the potential hazards that glass failure poses to people during a terrorist bombing.

*Photographs on this page illustrate performance of the blast curtain system evaluated. (Test series 6, window 3)*



*Pre- and Post-test exterior views of the window protected with Skyline Mills blast curtain system.*



*Looking into the reaction structure from the outside, these views show the trapped glass.*

